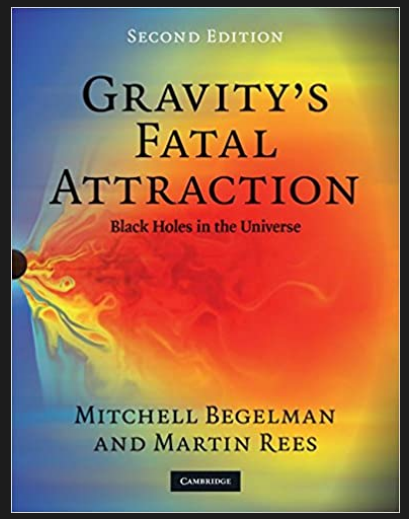
8: Galaxies, Nuclei & Quasars

Physics 17: Black Holes and Extreme Astrophysics

Goals

- Introduce different types of galaxy
- See how most galactic nuclei contain black holes
- Describe what happens when galactic nuclei became active
- Discuss the physical interpretation and consequences of this activity

Reading



Begelman & Rees

- Chapter 3: Discovery of black holes (p77-79, 95-101, 109-113)

Spiral Galaxies

- Young, blue stars
- Rich in gas and forming new stars
- Supported by rotation
- Disc with central bulge
- Dark matter
- Billions of solar masses
- 100,000 light years across

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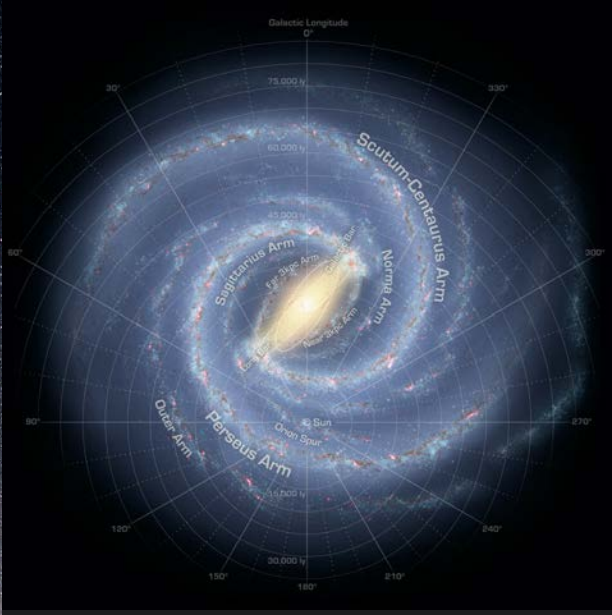
Sombrero Galaxy

Whirlpool Galaxy



The Milky Way
(seen from within!)

Elliptical Galaxies

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- Old, red stars
- Gas poor – “red and dead”
- Slowly rotating
- Dark matter
- Millions to 10 billion Solar masses

NGC 1316

NGC 4881

M87

Irregular Galaxies

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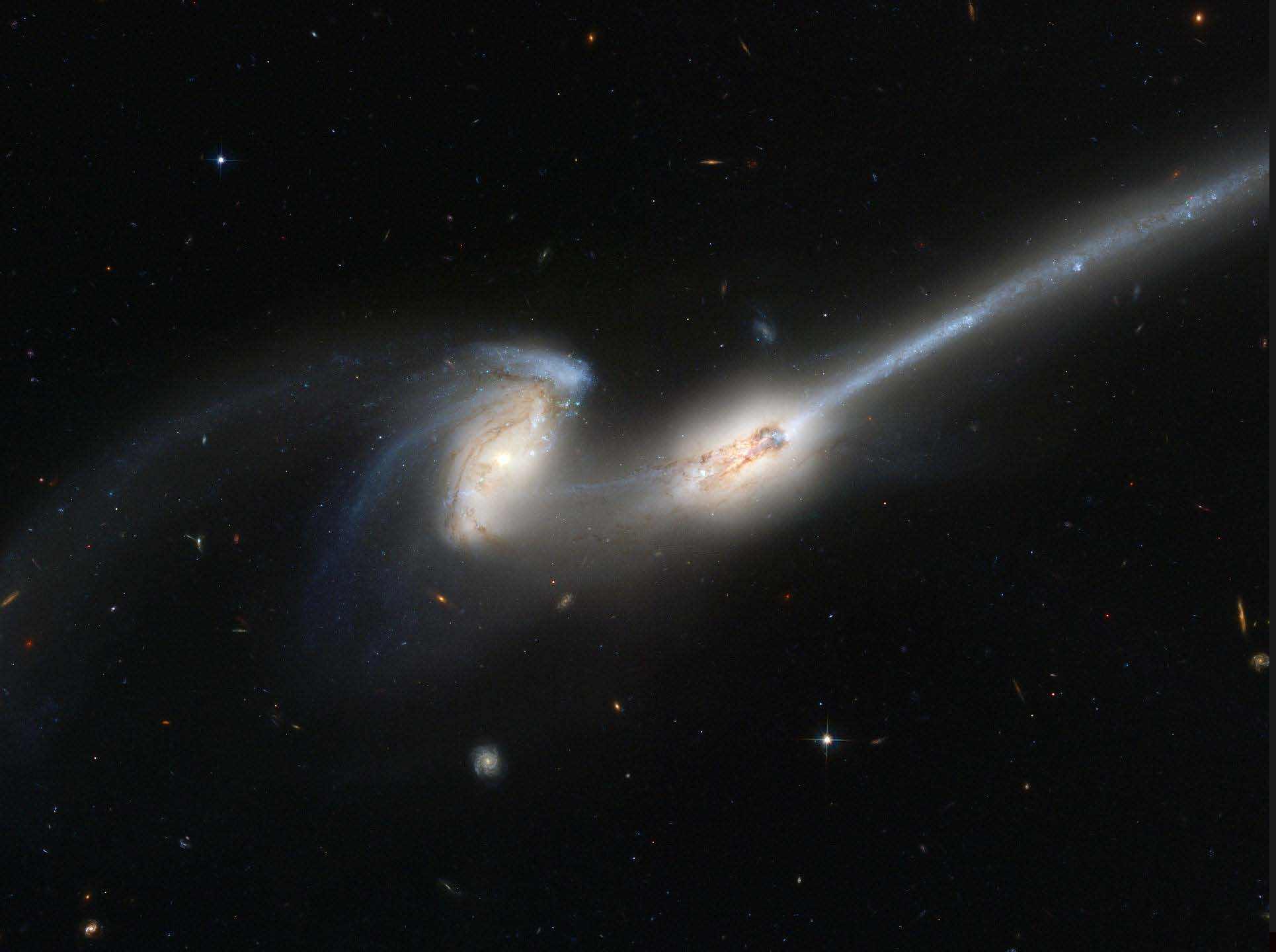
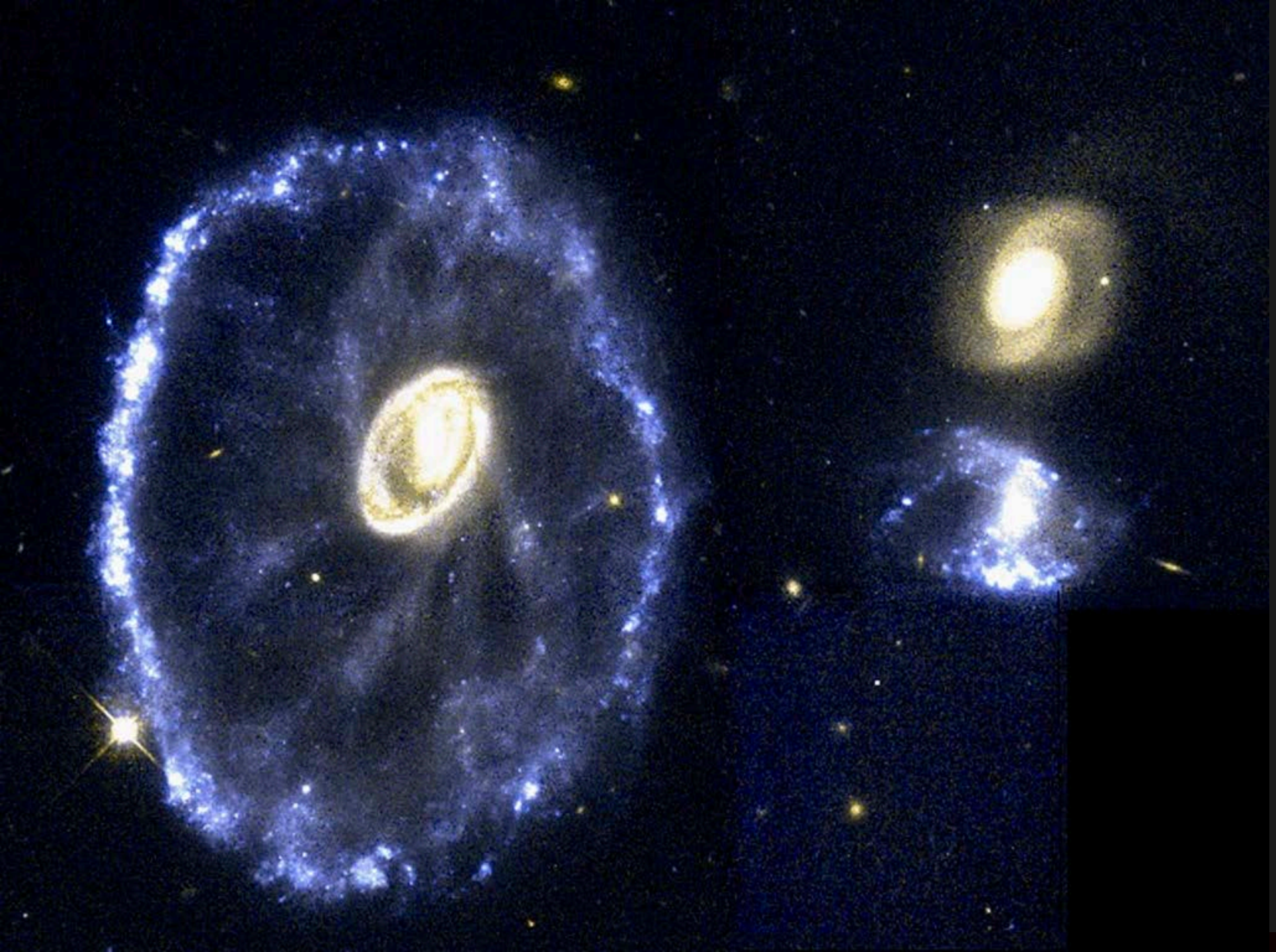
- Around 10% locally
- More than 50% when Universe was young
- Many show mergers
  - Spiral galaxies, pulled together by gravity, can merge, eventually forming an elliptical galaxy
- May be the building blocks of regular galaxies



The Mice



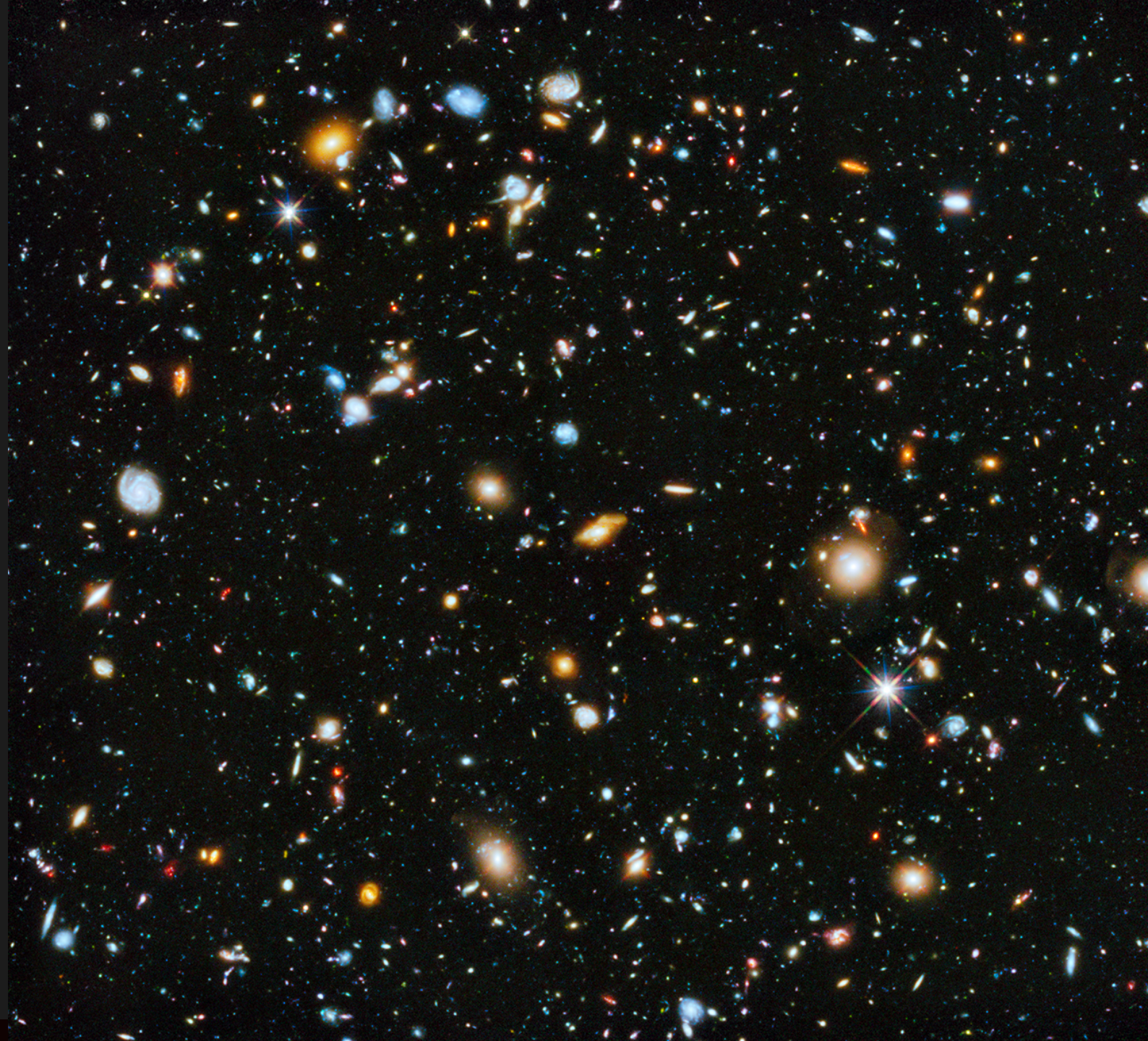
The Cartwheel

Mayall’s Object

Large and small Magellanic Clouds

Hubble Ultra Deep Field

- 12 days total exposure time of a small ‘empty’ patch of sky between known galaxies, 0.00001% of sky
- 10,000 galaxies seen
- 13 billion light years away
  - Light takes 13 billion years to reach us
- Some of the first galaxies that formed in the Universe



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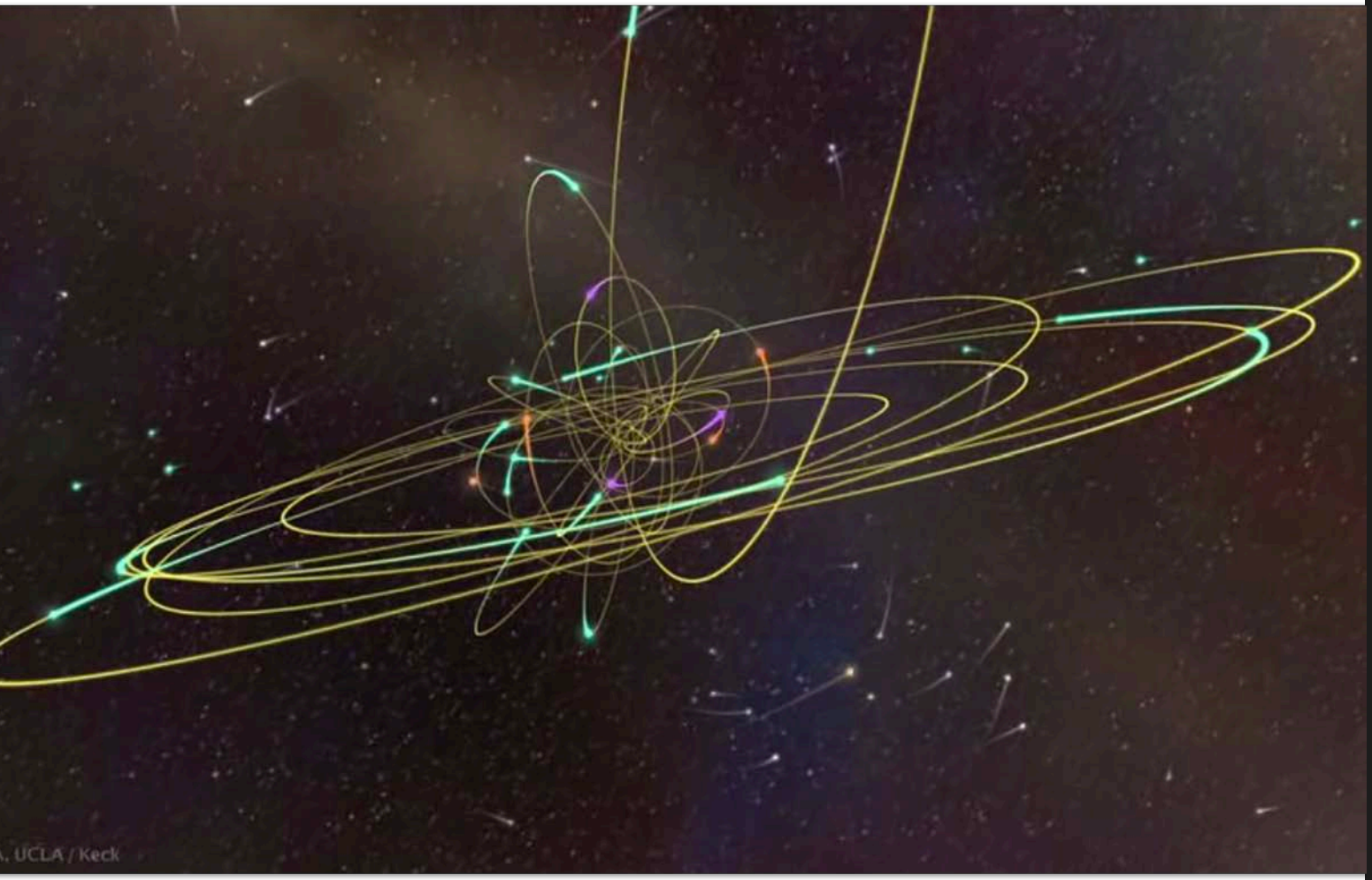
Galaxy Clusters

- Galaxies live in groups or clusters — the Milky Way is in the “Local Group” and our nearest neighbor is the Andromeda Galaxy
- Galaxy clusters comprise thousands of galaxies held together by their mutual gravitational attraction — the largest bound objects in the Universe
- Between the galaxies in a cluster, there’s a large quantity of gas, heated as the gravity from the galaxies pulls it in, as well as dark matter
- Dark matter > gas > galaxies!

The center of the Milky Way

Stars in the Galactic Center



Stars in the Galactic center are seen to travel in orbits

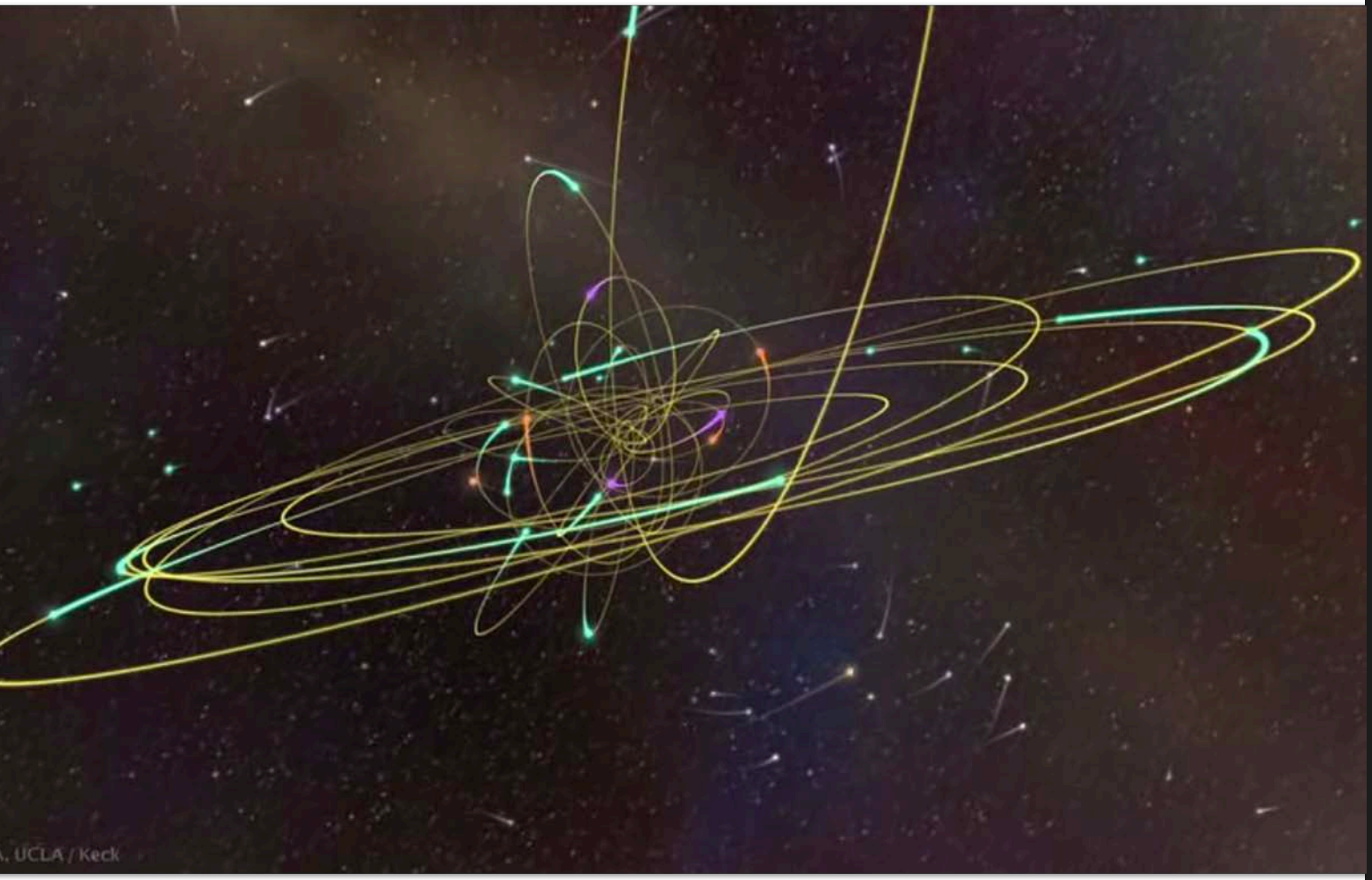
The star S2 in the Galactic Center is seen to make the closest approach to the focus of its orbit at a distance of 120AU, travelling at 7650 km/s.

What are the stars orbiting around?

Can you estimate the mass of this object?

QaD

Stars in the Galactic Center



Stars in the Galactic center are seen to travel in orbits

We can estimate the mass of the central object

$$\frac{GM}{r^2} = \frac{v^2}{r}$$

$$M \propto v^2 r$$

$$M \sim 7 \times 10^6 M_\odot$$

But the star is in an elliptical orbit so its velocity is faster than a circular orbit at closest approach

$$M \sim 4 \times 10^6 M_\odot$$

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Our Supermassive Black Hole

There is a supermassive black hole in the center of our galaxy (Sagittarius A* or Sgr A*)

$$M = 4{\times}10^6 M_\odot$$

We believe that most large galaxies (i.e. not dwarf galaxies) have supermassive black holes in the center

- How they formed is unclear
- Early population of short-lived, giant stars that merged into a supermassive black hole
- Direct gravitational collapse of millions of solar masses of gas to a black hole

Half of the 2020 Nobel Prize in Physics was awarded to Andrea Ghez & Reinhardt Genzel for the discovery of the supermassive black hole in the center of our Galaxy

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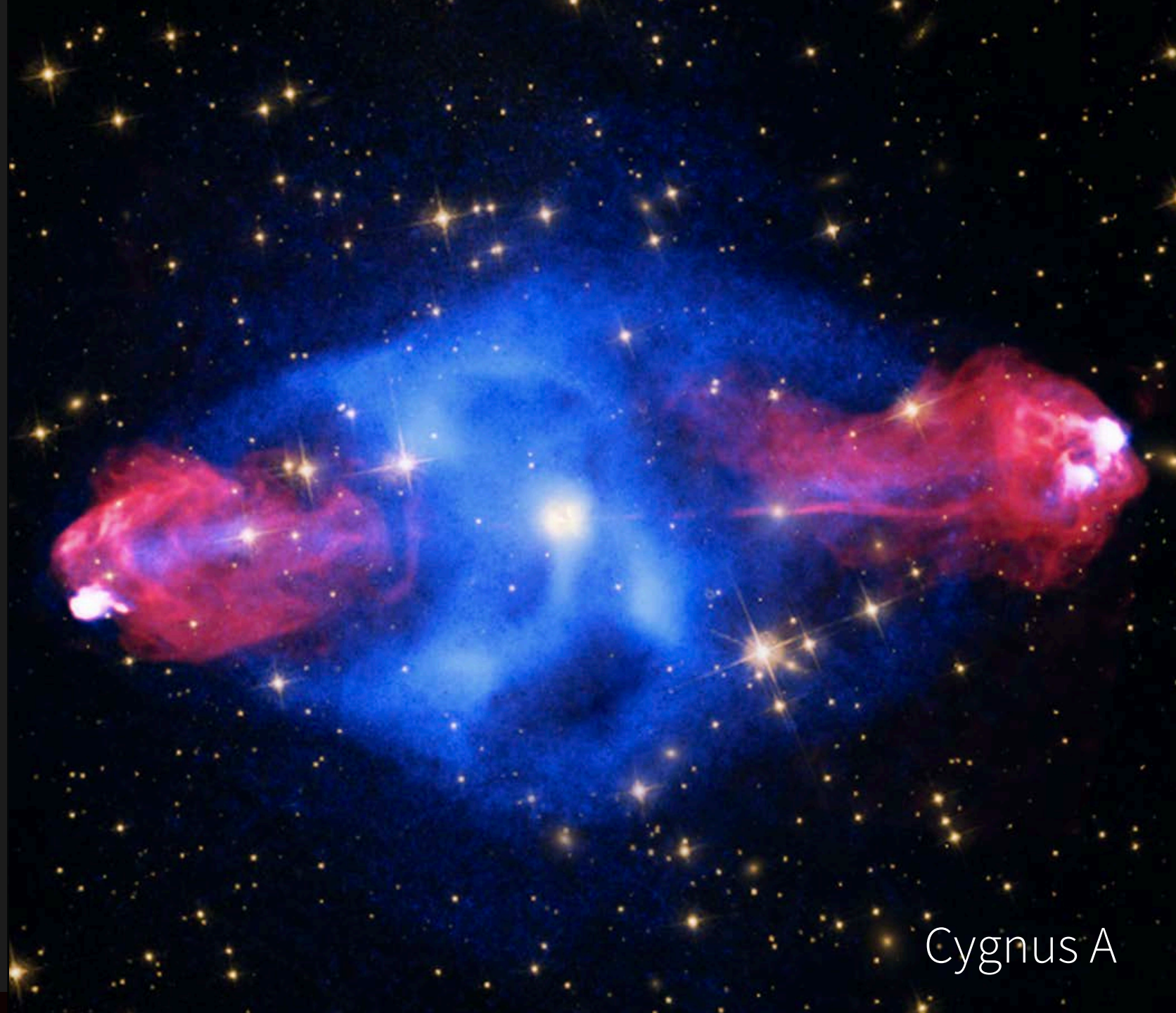
Radio Galaxies

Observing at radio wavelengths reveals high energy electrons and other charged particles moving in a magnetic field (synchrotron radiation)

The black holes in the centers of radio galaxies launch jets, travelling at almost the speed of light, that span hundreds of thousands of light years out of the galaxy

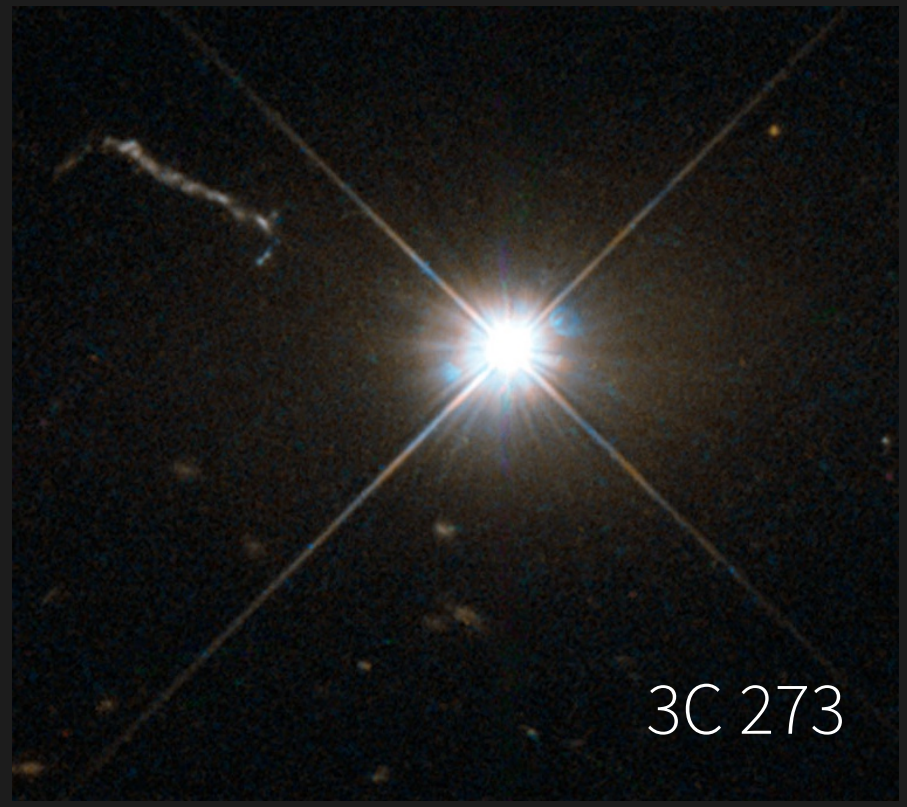
Jets carry large amounts of kinetic energy into their surroundings and inflate lobes as they hit the gas around a galaxy



Cygnus A

The Discovery of Quasars

- In a radio galaxy, we see the radio emission from the jets as well coming out of a galaxy that we can see
- In 1950s and 60s, another type of bright radio source was discovered that wasn't obviously associated with a galaxy
- Identified with "stars" of an unknown type

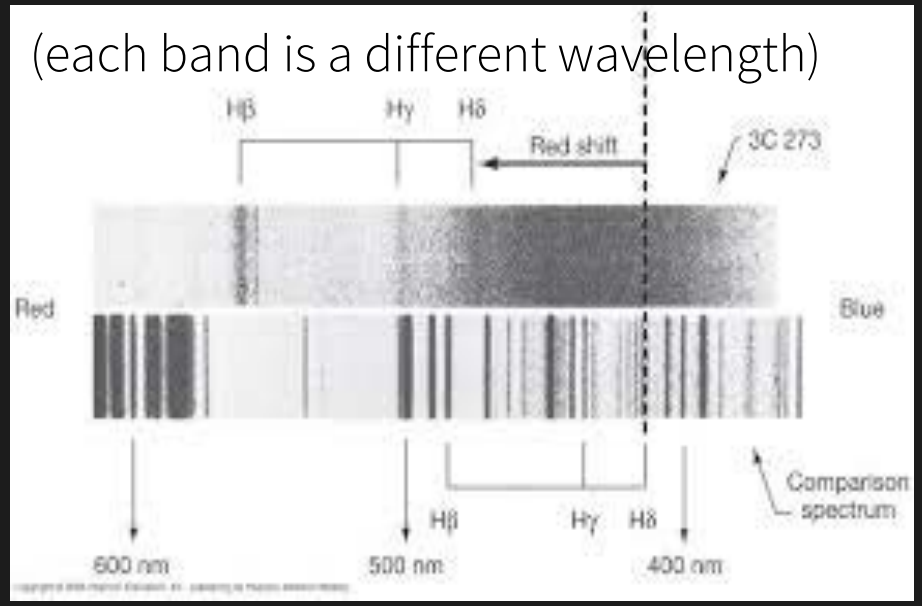


From their association with an unknown type of "star" they were called "quasi-stellar radio sources" or "quasar" for short

Quasars are Bright!

- Schmidt (1963) measured the spectrum of light from the quasar 3C 273
  - Shows strong emission lines from hydrogen (as in a star) but redshifted
  - Redshift shows 3C 273 is 2 billion light years away
  - To appear as bright as it does, it must therefore be 100x brighter than our entire Galaxy!
- Hazard (1962) found that the radio emission shows a point-like core (the 'star') and a jet
- Its brightness varies rapidly, so the emitting region must be small (Lecture 7) – about the size of the Solar System
- The only way we know to get so much power out of such a small region is from the energy released as matter falls into a supermassive black hole (Lynden Bell 1969)
- The black hole at the center of the galaxy is emitting so much power that it outshines the stars in the galaxy!

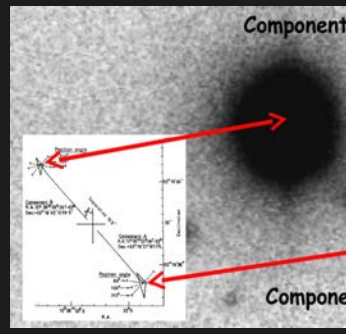
(each band is a different wavelength)

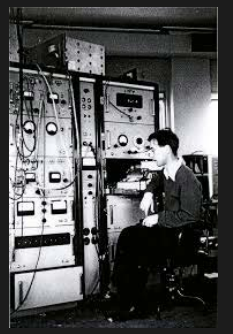


Light is redshifted as its emitter moves away from us (Doppler shift, Lecture 5).

The Universe is expanding. More distant objects move away from us faster (Hubble's law) WILtY

We can therefore estimate the distance of a galaxy by how much the light we see from it is redshifted





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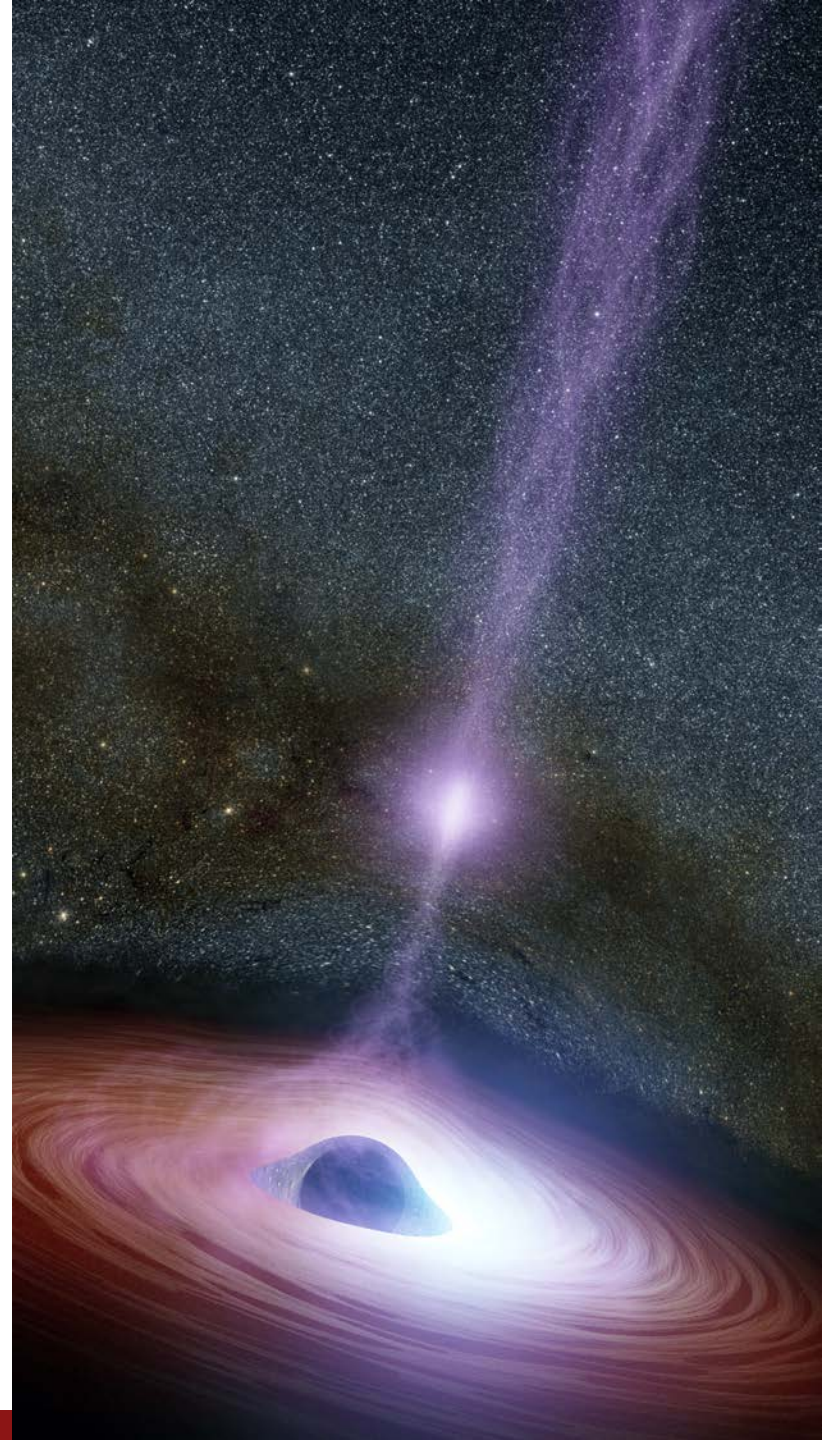
Quasars and Active Galactic Nuclei (AGN)

- Most galaxies have a supermassive black hole at their center
- In our galaxy, the black hole is quiescent
- In quasars and active galactic nuclei, a continuous supply of matter is falling into the black hole in the center of the galaxy
- Its gravitational energy is released as it spirals in through the accretion disc, powering the bright light source, X-ray source (corona) and jet (see Lecture 7)
  - The brightest continuous sources of radiation we see in the Universe



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AGN play an important role

- The light emitted by an active galactic nucleus (AGN) can outshine the stars in a galaxy
- The total energy output of an AGN (the sum of the radiation and the kinetic energy in jets and winds) exceeds the gravitational energy holding the stars in a galaxy
- If you could put all the energy coming out from the nucleus into the stars, you would blow the galaxy apart!
- This means that the AGN must have played an important role in governing the growth of the galaxy
- As the galaxy tries to grow from gas falling into it, the black hole is also growing and its power output gets stronger, pushing the gas away. The black hole stops the galaxy getting too big (AGN feedback)

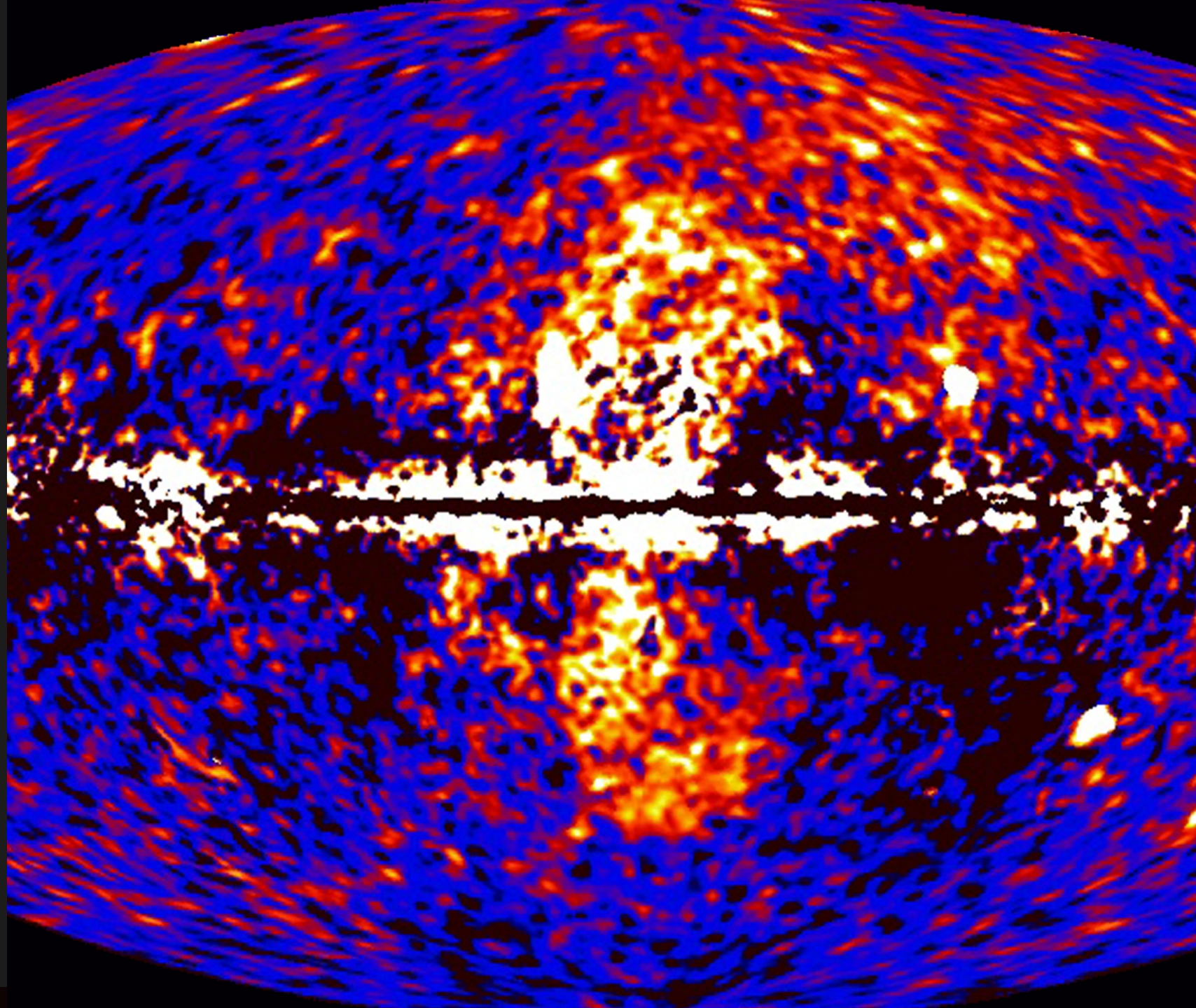
In NGC 1275, the galaxy in the center of the Perseus cluster, we see AGN feedback in action. The black hole in the center of the galaxy launches jets that inflate bubbles in the gas that surrounds the galaxy.

Our galaxy might once have been active

The Fermi gamma ray observatory found extended “bubbles” centered on the Galactic center, Sgr A*

It is believed these are due to past activity from the black hole, perhaps launching its own jets. The bubbles are the “echoes” of the emission from the jets which have now stopped.

It is likely that all Galactic nuclei go through an active phase while the galaxy is growing



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- Spiral, elliptical and irregular galaxies
- Galaxies are pulled together by gravity and grow by merging
- Galaxies have a supermassive black hole in their nuclei, millions of solar masses
- Material falling into the black hole at the center of a galaxy powers the the brightest continuous sources of radiation we see in the Universe – active galactic nuclei (AGN), quasars, radio galaxies
- AGN played an important role in the growth of galaxies and structure in the Universe